Trends in Anaesthesia and Critical Care 36 (2021) 23–29

Contents lists available at ScienceDirect

Trends in Anaesthesia and Critical Care

journal homepage: www.elsevier.com/locate/tacc

Review

Speech intelligibility in respiratory protective equipment - Implications for verbal communication in critical care

Matthew Round [a,*], Peter Isherwood [a]

[a] University Hospitals Birmingham NHS Foundation Trust, UK

ARTICLE INFO

Article history:
Received 19 July 2020
Received in revised form
12 August 2020
Accepted 13 August 2020

Keywords:
Respiratory protective devices
Personal protective equipment
Speech intelligibility
Verbal communication
Human engineering ergonomics
COVID-19

ABSTRACT

Respiratory protective equipment (RPE) such as filtering facepiece respirators, elastomeric respirators and powered air-purifying respirators are routinely worn in the critical care unit as a component of personal protective equipment (PPE) when caring for patients with coronavirus disease 2019 (COVID-19). It is the authors' anecdotal experience that RPE may, however, inadvertently interfere with verbal communication between critical care staff. The literature pertaining to the effects of RPE wear on verbal communication was therefore reviewed. A literature search returned 98 articles, and 4 records were identified from other sources; after screening for content relevancy, 15 experimental studies were included in the narrative synthesis. Previous studies in both healthcare and other occupational settings suggest a detrimental impact on speech intelligibility, varying according to RPE type and test conditions. The effects of background noise and potential for increased cognitive load through compensatory behaviours are also identified. The clinical significance of these effects remains uncertain though, as evidence measuring clinical outcomes or errors is lacking. Mitigating strategies include increasing speech intelligibility through environmental changes and technology; modifying verbal communication strategies; and decreasing reliance on verbal communication where possible.

Contents

1. Introduction

Personal protective equipment (PPE) has become a focal topic during the coronavirus disease 2019 (COVID-19) pandemic, with routine sessional use attaining normality in critical care units worldwide. Respiratory protective equipment (RPE) - a component

* Corresponding author. Department of Anaesthesia and Critical Care, University Hospitals Birmingham NHS Foundation Trust, Birmingham, B15 2GW, UK.
E-mail address: matthew.round@nhs.net (M. Round).

https://doi.org/10.1016/j.tacc.2020.08.006
2210-8440/

of PPE - aims to protect healthcare workers (HCW) from occupational exposure to respiratory pathogens, and to reduce disease transmission that might otherwise be potentiated by infected staff.

Indirect transmission of respiratory pathogens may be via droplets (>5 μm) that rapidly settle out of the air, or aerosols of particles (<5 μm) that can remain airborne for longer periods. Loose-fitting fluid-resistant surgical masks (FRSM) provide a barrier against droplet transmission, whilst respirators protect the wearer against airborne transmission through mechanical filtration. Both types reduce the spread of respiratory viruses [1–3]. HCWs may encounter different forms of respirators. The filtering facepiece respirator (FFR or FFP) is a close-fitting disposable mask, of which common standards include the FFP3 in Europe and N95 in the United States. The reusable elastomeric respirator - either half-mask (covering the mouth and nose) or full-face - may be used with appropriate particulate filters. The powered air-purifying respirator (PAPR) does not require a tight seal with the wearer's face, rather it relies on a constant flow of filtered air within a 'hood' [4,5].

The 2003 Severe Acute Respiratory Syndrome (SARS) epidemic and the 2009 influenza A H1N1 'swine flu' pandemic stimulated widespread use and study of respirators in HCWs, having previously seen sporadic service for indications such as tuberculosis and aerosol-generating procedures (AGPs) in influenza [3,6,7]. The transmission route and necessary RPE for COVID-19 have been debated, with international variation in guidance and standards [4,8]. Airborne precautions are nonetheless prudent in the early phases of emerging outbreaks before the transmission route is determined. Public Health England recommends sessional use of airborne RPE in high-risk areas like critical care where AGPs such as tracheal intubation are performed [9].

RPE may, however, have unintended impacts for those wearing it. Previous publications have qualified HCW perceptions of respirators [10–13]. Following their 1992 recommendations in relation to tuberculosis, the United States National Institute for Occupational Safety and Health (NIOSH) faced objections from doctors due to fears that the stipulated PAPR equipment looked frightening, could interfere with communication, and may deter patients from seeking healthcare [14]. Experiences reported after SARS reiterated concerns regarding communication, though these tended to focus on the therapeutic relationship rather than communication between staff [10,11,15]. Almost half of surveyed hospital staff chose 'difficulty communicating' as a reason for finding masks bothersome [16]. Another study found under 10% of surveyed HCWs reported they could speak normally whilst wearing a PAPR, with over a quarter having to raise their voice significantly [12]. In a prospective study of staff wearing respirators for prolonged periods, diminished communication ability accounted for 21% of the reasons given for discontinuing use sooner than the planned 8-h session [13].

Intelligibility refers to the quality of speech transmission and resulting comprehensibility. It has complex influences including amplitude and frequency components of the sound, distortions, ambient noise, and psychoacoustic effects. It is often measured using single words, which provide the least redundancy for transmission. Words in sentences are more accurately comprehended than the same words in isolation, as masked sounds may be interpolated within the wider language context. Other contextual hints such as repetition of words or limiting vocabulary can also increase intelligibility [17,18].

The Speech Transmission Index (STI) is a measure of intelligibility calculated from signal-to-noise ratios at certain frequency bands to predict the likelihood of correct verbal comprehension on a scale of 0 (no transmission) to 1 (perfect transmission). An STI value ≥ 0.6 is classed as good intelligibility, whilst ≥ 0.75 is excellent. A similar measure - the articulation index (AI) - predicts the proportion of speech sounds a listener will correctly perceive. Sentence intelligibility remains high so long that the AI is approximately 0.4–0.5, though where accurate transmission of single words is important a higher AI would be necessary [19,20].

In our centre - a large critical care unit within a tertiary hospital - staff have anecdotally expressed perceived difficulties in communication when wearing airborne RPE during the care of COVID-19 patients, necessitating repetition and modification of verbal information. Masks may alter sound transmission, impede jaw movement and hide visual cues such as lip reading and facial expressions [21,22]. Verbal communication is vital in critical care, and this may potentially have an impact during critical tasks such as information transfer during shift handovers and team coordination during emergency scenarios [23–25].

2. Aims

We aimed to review the literature on the effects of respiratory protective equipment on speech intelligibility and verbal communication, and to synthesise the findings as relevant to the critical care setting. These may include the presence and magnitude of any effects, and factors that could influence them.

3. Methods

A non-systematic literature review was conducted. A literature search was carried out in MEDLINE (Ovid) from database inception to May 21, 2020. This was supplemented by a Google search for relevant articles, governmental and institutional reports. The full search strategy is included in Appendix A. Citations were manually searched for additional sources. Titles and abstracts were screened by the primary reviewer (MR) for any studies reporting assessment of verbal communication or speech intelligibility with respiratory protective equipment (and related keywords); full-text articles were assessed (MR) and deemed eligible for inclusion if they compared such characteristics with a non-RPE control through any experimental methodology. No limits were placed on study setting, as those from non-healthcare contexts may still yield translatable findings. No temporal, geographic or language exclusion criteria were applied. Pertinent findings relevant to the review aims were summarised in a narrative synthesis for subsequent discussion.

4. Results

The database search returned 98 articles, and 4 additional records were identified through other sources. After screening titles and abstracts for content relevancy, 87 were excluded and 17 full text-articles were assessed for inclusion in the narrative synthesis. Two articles [26,27] were excluded as they did not make comparisons with non-RPE controls. A flow diagram is provided (Fig. 1) for this process.

Two broad themes were apparent in the 15 included articles: 12 studies reported measurement of RPE characteristics such as speech intelligibility in isolation; whilst 3 assessed the impact of PPE (including RPE) on verbal communication during simulated task performance. A summary of these studies is provided (Table 1).

4.1. Measured speech intelligibility

Speech intelligibility through RPE was studied as early as 1961 when, in the industrial setting, it had been noted that workers in toxic atmospheres were removing masks to talk. Fawcett tested the AI of common RPE devices and concluded that communication in a noisy environment would be impaired whilst wearing many of these, and that intelligibility characteristics must be appreciated

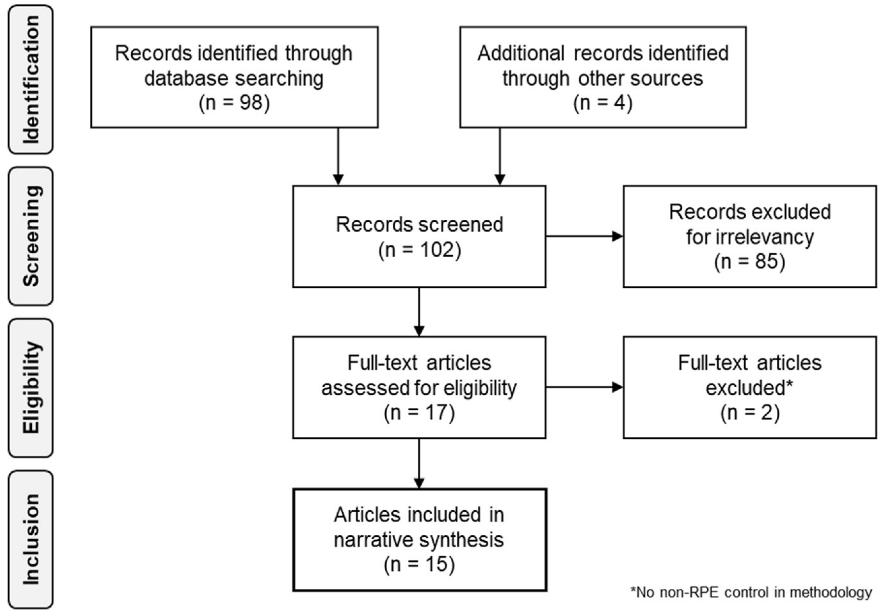

Fig. 1. Flow diagram for article selection process.

when appraising RPE [19]. Integrated telephones or radios were suggested as a workaround. A similar evaluation of various industrial and military respirators over 50 years later found none to meet U.S. military criteria for normal acceptable intelligibility (requiring performance characteristics suggestive that single digits and around 98% of sentences would be heard correctly) [28].

Another industry-focused study evaluated the effects of a military full-face respirator on single-word and sentence comprehension at varying distances [21]. A performance rating was calculated from each test score with the respirator as a percentage of a paired score without. Single-word comprehension degraded to 0% by 9.15 m, whilst sentence comprehension was preserved at 74.2% at the same distance; highlighting the disparity between word and sentence intelligibility under similar conditions.

A further study from the same journal assessed the effects of background noise and speech diaphragm size on intelligibility with full-face respirators [29]. A speech diaphragm is a vibrating membrane added with the aim of improving speech transmission. Though no difference was found between speech diaphragm conditions, background noise as tested at three levels was found to have a significant effect. The decrease in intelligibility with increasing noise was greater for respirators compared to no-mask controls, suggesting a negative synergistic impact on communication in RPE.

During pandemic influenza planning, the Federal Aviation Authority evaluated the performance effects of N95 and PAPR use relevant to air traffic control operations [30]. Both respirator types decreased face-to-face intelligibility, with error rates for the PAPR exceeding acceptable levels. When measured for different conditions of speaker and listener RPE use, more errors occurred when the speaker wore RPE regardless of the listener condition, implying the communication impairment was occurring on the speaker's side. Participants also reported adjusting breathing patterns to reduce noise interference for listening tasks.

Specific to the healthcare setting, a 2008 study [31] aimed to evaluate the effect of surgical masks on word identification in environments with and without simulated background noise. 30 listeners were presented with recordings of word lists spoken with and without a mask; though the frequency spectra of recordings were different, this did not translate to a demonstrable effect on word identification accuracy. Independent of mask use and hearing impairment; a significant, albeit small, difference between the tests with and without background noise was shown. The study was arguably limited by its use of recordings from a single voice artist who was noted to speak in an *"extremely articulate and clear manner"*. A transparent surgical mask was subsequently tested; visual input - whether from the transparent mask or no-mask - appeared to benefit listeners with hearing impairment, though subjects with normal hearing performed highly regardless of test condition [22].

In 2010, Radonovich et al. tested the intelligibility associated with RPE worn by HCWs (16 nurses) in actual and simulated intensive care unit (ICU) environments [32]. The NIOSH modified rhyme test (MRT) was used: a validated tool that requires listeners to identify the correct answer from six rhyming words. Tests were performed at 3 and 7 feet separation between speaker and listener, representing the typical dimensions of an ICU bed. Disposable respirator reuse including shrouding with an FRSM to reduce exterior contamination had been suggested to prevent shortages [33], and therefore this scenario was also tested. A varied negative impact on word identification accuracy according to RPE type was demonstrated with absolute scores decreasing by 1%–17% compared to controls (no RPE); only tests for PAPR, valved FFR with overlying FRSM, and half-mask elastomeric respirators reached statistical significance. The valved FFR (3 M 8511) with overlying FRSM in the actual ICU environment was associated with a drop in MRT accuracy from 89% to 82%; the odds ratio of correct word identification wearing this combination compared to controls was calculated as 0.53 (95% CI 0.36–0.77, $p = 0.006$). Notably, control test accuracy in the actual ICU environment was lower (89%) than in the simulated ICU environment (97%); reverberation, psychoacoustic effects, and distractions were suggested to underlie this difference. This demonstrated a potential baseline of impaired verbal communication in the ICU before RPE is even introduced, and the importance of ensuring experimental conditions closely represent the intended real-world application. The study also explored hearing impairment from PAPR use; with speakers not wearing RPE, average MRT accuracy decreased from 90% to 79%

Table 1
Summary of included studies.

Reference (Year)	Journal/Source	Sample [Setting]	RPE Type	Methodology	Independent Variables	Relevant Findings
Fawcett (1961) [19]	Am Ind Hyg Assoc J	1 speaker [non-healthcare]	8*x* respirators, 7*x* other (e.g. self-contained breathing apparatus)	AI[a] calculated from recordings for: (1) office area at 10 ft separation; factory area at (2) 1 ft & (3) 2 ft separation.	RPE type	AI 7–80% of control, varying by type (28–80% for respirators). Most types satisfactory for sentence intelligibility in quiet area, but would impede even close-range communication in noisy setting.
Coyne et al. (1998) [21]	Am Ind Hyg Assoc J	13 speakers, 13 listeners [non-healthcare]	Full-face (U.S. Army 'M-17')	MRT[b] (single-word) & SPIN[c] (sentence) face-to-face, speaker & listener both wearing respirator.	Separation distance (0.61–12.2 m)	Greater impact of distance on single-words than sentences; single-word accuracy fell to 0% by 9.15 m. At 0.61 m, performance ratings 92.2% (sentence) & 79.8% (single-word) vs. controls.
Johnson et al. (2000) [35]	Am Ind Hyg Assoc J	22 subjects [non-healthcare]	Full-face (U.S. Army 'M-40')	MRT[b] over telephone.	Speech diaphragm, protective hood *(industrial/military context)*	*Limited applicability of main findings to healthcare setting.* Baseline 1% error rate in controls. 46% of errors involved words containing letter 'p'. Noted handsets held still when talking.
Johnson et al. (2001) [36]	Am Ind Hyg Assoc J	24 subjects [non-healthcare]	Half-mask elastomeric, full-face & PAPR	MRT[b] over telephone.	RPE type, telephone protocol (moving handset & ending with 'over')	Baseline 2.5% error rate in controls. Without telephone protocol, reduced accuracy for all RPE vs. controls. 5–10% improvement in accuracy when telephone communication protocol used.
Caretti & Strickler (2003) [29]	Am Ind Hyg Assoc J	35 subjects [non-healthcare]	Full-face (unspecified)	MRT[b] face-to-face, speaker & listener 3m apart + differing levels of noise.	Background noise, speech diaphragm area modification	Significantly greater decrease in intelligibility with increasing noise in respirator group vs. controls. No difference with speech diaphragm area.
Coniam (2005) [41]	Lang Assess Q	186 subjects [non-healthcare]	Surgical mask	School oral examination: objective performance in exam scores; subject & examiner questionnaires.		No significant differences in scores with or without masks. Lower perceived performance with masks. Some subjects reported compensatory behaviours such as speaking slower & louder, attempting more eye contact & body language.
Udayasiri et al. (2007) [39]	Emerg Med Australas	18 subjects [healthcare]	Full-face (part of 'level C' PPE)	Recall of simulated 10-point handover (objective accuracy & subject-rated performance on 10-point VAS[d]).		No objective difference between PPE and control groups (80% accuracy in communication task for both), though subject-rated performance fell from 8.9 to 6.0 in PPE.
Hah et al. (2008) [30]	U.S. Department of Transportation Federal Aviation Administration	'Phase two': 9 subjects [air traffic control]	3*x* PAPR, 3*x* FFP (N95)	MRT[b], radio headsets (PAPR) & face-to-face (FFP).	RPE type, wear combinations (both, speaker-only, listener-only, none)	Error rates: PAPR 3–18%; N95 0–16%; controls 0–4%. More errors when speaker wore PAPR, regardless of listener condition.
Mendel et al. (2008) [31]	J Am Acad Audiol	1 speaker, 30 listeners [healthcare]	Surgical mask	CST[e] from recordings ± simulated dental office noise.	Hearing impairment, background noise	No difference between mask & no-mask (regardless of hearing impairment). Small difference with & without background noise.
Radonovich et al. (2010) [32]	J Occup Environ Hyg	16 subjects [healthcare, intensive care unit (ICU)]	FRSM, FFP, half-mask elastomeric & PAPR	MRT[b] face-to-face: (1) speaker wearing RPE in actual ICU; (2) speaker wearing RPE in simulated ICU; (3) listener wearing PAPR in simulated ICU.	RPE type, ICU environment	1–17% decrease in intelligibility vs. controls, varying by speaker RPE type: significant effect for half-mask respirators & some FFP types. Negative impact from listener wearing PAPR. Lower performance in actual vs. simulated ICU: 89% MRT baseline in actual ICU controls.
Thomas et al. (2011) [37]	Air Med J	1 speaker, 3 listeners [healthcare]	FRSM, FFP (N95)	Custom protocol (aviation terms) spoken over radio by pilot, medical helicopter.	RPE type, helicopter engine noise	Without engine noise: 100% accuracy regardless of RPE type. With engine noise: 100% accuracy with FRSM & 2*x* N95 models, 93–98% accuracy in remaining 4*x* N95 models.
Coyne & Barker (2014) [28]	J Occup Environ Hyg	72 subjects [non-healthcare]	12*x* full-face	MRT[b].	RPE type	All met 70% performance rating required by NIOSH. None met U.S. military criteria for normally acceptable intelligibility (MRT ≥91%).
Palmiero et al. (2016) [34]	J Occup Environ Hyg	n/a [laboratory]	FRSM, FFP & half-mask elastomeric	STI[f] calculated from test tones.	RPE type	FRSM: mean STI 0.78–0.79 (excellent). FFP: mean STI 0.71–0.72 (good). Half-mask: mean STI 0.45–0.48 (poor/fair).
Atcherson et al. (2017) [22]	J Am Acad Audiol	1 speaker, 30 listeners [healthcare]	FRSM (standard & transparent)	CST[e] from audio-visual recordings + background noise ('4-talker babble').	Hearing impairment, visual input	≥99% performance for normal hearing group in all conditions. Hearing-impaired groups benefitted from visual input with no-mask or transparent mask, but not with standard mask.
Schumacher et al. (2017) [40]	Anaesthesia	30 subjects [healthcare, anaesthetics]	PAPR & full-face (part of CBRN[g] PPE ensemble)	Subject-rated speech intelligibility on 6-point VAS[d] during simulation.	PPE ensemble	Lower intelligibility rating for ensemble using PAPR (1.1) vs. full-face respirator (3.6); ratings for control group not published.

[a] AI: Articulation Index.
[b] MRT: Modified Rhyme Test.
[c] SPIN: Speech Perception In Noise.
[d] VAS: Visual Analogue Scale.
[e] CST: Connected Speech Test.
[f] STI: Speech Transmission Index.
[g] CBRN: Chemical, Biological, Radiological and Nuclear.

when listeners wore a PAPR.

When RPE has been evaluated in a laboratory setting (using test tones played through a specialist manikin wearing a variety of masks), FRSM were found to have excellent STI, FFR/FFP good STI, and elastomeric half-mask respirators poor/fair STI [34]. By cross-referencing their measured STI of a particular FFR at 0.71 with the findings of Radonovich et al. (showing no significant difference in intelligibility when the same FFR was compared to controls), an STI of $\geq$0.70 was proposed as a baseline for future healthcare PPE.

Another facet of verbal communication in critical care is telephone communication to other staff and patient relatives. When assessing telephone communication with military full-face respirators (also worn with protective hoods), MRT accuracy was degraded by about 10% compared to non-PPE controls [35]. Subjects were noted to keep the telephone handset against their ear, and not move the mouthpiece towards the exhalation valve when speaking. The military equipment used in this study limits its relevance to a healthcare setting, though the same team subsequently extended their work to other RPE, including PAPR and half-mask models also used in healthcare [36]. Following the observations about handset use, a protocol was tested whereby the handset was moved from ear to mouth when speaking, and the proword *"over"* used to complete each message; this intervention resulted in statistically significant improvement in performance, though a coaching effect could not be excluded. Telephone response time was also found to be impaired by RPE, taking 30–50% longer [35,36].

Lastly, a small study of 1 speaker and 3 listeners attempting radio communication in an emergency medical helicopter setting was unable to demonstrate significant effects of RPE on word identification accuracy, though the authors conceded it was underpowered to do so. Relevant findings were suggested however; errors only occurred with the helicopter engines on, again highlighting the role of ambience noise and environmental factors in verbal communication. Additionally the layperson listener made the most identification errors, supporting the concept that contextual and language familiarity contributes to speech intelligibility [37].

4.2. Communication during task performance

The second broad theme of studies identified were those that assessed the impact of PPE on the ability to perform various tasks, for which verbal communication may be a component. It has been described that work cannot usually be performed as long or as hard while wearing a respirator; either more time or more workers must be allowed for the same task [38].

Udayasiri et al. evaluated performance of emergency department trauma resuscitation tasks whilst wearing PPE (with a full-face respirator), including listening to and recalling an ambulance handover. Despite perceived communication performance (self-reported on a visual analogue scale) falling significantly between unsuited and PPE simulations, no difference was measured in their accuracy scores. However the order of the tests was kept the same, meaning the initial unsuited scenario possibly allowed participants to gain familiarity with tasks. It was also suggested that extra effort and concentration were expended to achieve the same result, but that this compensation may *"reach a critical limit in a disaster situation"* [39].

Similar methodology has been used since to compare the performance of advanced resuscitation tasks by anaesthetists in two different sets of 'chemical, biological, radiological or nuclear substance' PPE. Treatment times were longer in PPE groups (149 and 204 s) compared to non-PPE controls (116 s). Unfortunately, wearer-rated speech intelligibility - collected as a post-scenario questionnaire - was only reported for PPE groups and not compared with controls [40].

Though outside the healthcare setting and not demonstrating a performance impact from surgical mask wear, both students and examiners in a high school oral examination experiment reported adopting compensatory adjustments when wearing masks such as altering their speech (loudness, rate or articulation), eye contact and body language; again these behaviours may compound cognitive load and fatigue [41].

5. Discussion

These studies in healthcare and other sectors highlight the potential for reduced speech intelligibility associated with RPE. Most studies demonstrated a detrimental impact of RPE, and where a difference was not proven this was often proposed to be due to methodological limitations rather than evidence of absence. Whilst strong direct evidence of reduced communication-related task performance in RPE is lacking, the existing studies illustrate the scope for increased fatigue and time required to communicate or complete tasks when wearing RPE. These are all important considerations for the safe provision of critical care in the COVID-19 era.

It must be recognised that all studies used small samples of participants with consequently restricted characteristics, whereas in real-world healthcare settings there are diverse variations in speech, hearing, environment and task-associated cognitive load that may result in speech transmission, reception and processing markedly different to that suggested by these studies. These studies also did not utilise medical language with its associated risks of misinterpretation; e.g. *"microgram"* and *"milligram"*. Lastly, it is difficult to account for compensatory behaviours such as breathing adjustments and the Lombard effect - the involuntary increase in speech loudness & pitch in noisy environments [42]. Whilst these compensations overcome difficulties for short-term wear, they are likely to be fatiguing for extended use and add to extraneous cognitive load; the risk of cognitive overload resulting in decreased attentional capacity in high-pressure decision-making may have important clinical consequences [43].

This review is itself limited by its non-systematic nature, small number of studies identified and limitations thereof. The literature search considered RPE as whole, consolidating different RPE types with heterogeneous effects including some from military settings; multiple types and models may be found in concurrent use in the same critical care unit though, so an overview of the spectrum of impact should still be of valid interest to the critical care clinician. The diverse range of settings, methodology and interventions precluded any quantitative synthesis. Lastly, while communication failures will intuitively contribute to medical errors, the clinical significance of reduced intelligibility associated with RPE is unknown; as no studies of communication interference from RPE have used clinical outcomes these discussions therefore remain inferential.

Overall we have seen that intelligibility is a complex entity to measure, and a continuum that fluctuates according to content and context for even otherwise fixed conditions, but which RPE does appear to degrade. Concurrently we should acknowledge that information transfer in critical care - even without RPE – even without RPE – is imperfect [32]. Therefore how do we set an acceptable level of intelligibility and consequential risk for verbal communication - is fair sentence intelligibility adequate, or should we aim for syllabic perfection?

NIOSH requires respirators to achieve an MRT performance rating $\geq$70% to meet minimal approval requirements for occupational use. Higher single word accuracy is arguably necessary for critical care; mishearing of an allergy, emergency instruction, drug dose or airway information could lead to misdoing and harm. Thomas et al. [37] suggested that even a small reception error could be 'operationally meaningful' and compromise safety in the HEMS context. Intermediate speech degradation may also be more dangerous than a complete loss of communication, as the former may lead to an incorrect action whereas the latter likely results in no action [44]. It may therefore be appropriate to look to the U.S. military criteria; these normally require an absolute MRT score of at least 91%, equating to high sentence and single digit intelligibility [28].

Assuming we should strive for maximal accuracy, we propose three principal strategies for critical care units:

1. Increase intelligibility through improved RPE design, wireless communication systems and reduced background noise
2. Modify verbal communication structure to mitigate risks, such as utilising radiotelephony procedures, readbacks and NATO phonetic alphabet
3. Decrease reliance on verbal communication, via written handovers, management plans and orders

A survey following the 2009 H1N1 pandemic indicated that RPE needed to be modified to meet the requirements of HCWs [45]. The 2014 Project BREATHE (Better Respiratory Equipment using Advanced Technology for Healthcare Employees) [46] proposed a new class of *"B95"* (biological) respirators with characteristics optimised for healthcare, including that they should not impede - and preferably improve - speech intelligibility. Transparent materials to allow facial visualisation were also suggested; an idea that has been demonstrated with surgical masks [22], though the technical feasibility of transparent respirators remains unclear. Regardless, this new generation of respirators unfortunately did not materialise.

Some existing respirator designs feature voice augmentation devices such as speech diaphragms or electronic amplifiers, but these have been shown to only partially mitigate communication interference [29,32]. Wireless communication may offer a route to enhanced verbal communication in RPE. Bone conduction technology - shown to outperform mask-mounted air conduction systems in the military setting [47] - could be applied for both directions of signal transduction, overcoming challenges of placing a microphone near the mouth and maintaining environmental hearing and awareness by not blocking ear canals.

RPE and other head-borne PPE may also have additional relevant impacts on human factors and ergonomics that warrant further investigation in the healthcare setting. One effect that may be observed when ears are covered is a 180-degree 'front-to-back' confusion of sound localisation; in the ICU setting, this could result in looking and moving away from an emergent shout for 'help' [48].

Expanded in-situ and ICU-specific testing of RPE should be conducted. Whilst quantifying effects on errors and clinical outcomes may be unfeasible, existing methodology could be adapted with medical terminology and COVID-19 ICU tasks. Information transfer and errors during patient handovers could be evaluated, as these are particularly known to be vital communication-driven events with demonstrable effects on mortality, length of stay and staff satisfaction [49].

6. Conclusion

RPE is not new to the critical care unit, however never has its use been so widespread and essential. RPE can impact speech intelligibility, though the knock-on effects and clinical significance of this remains undetermined. Past proposals have been made for improved healthcare-specific RPE, but the desired characteristics are perhaps too idealistic and progress appears halted. Working with existing RPE designs, we can still take steps to mitigate their impact. This may be through modified communication and handover practices, adoption of available technologies such as wireless voice systems and bone conduction headsets, or a combination of techniques. We should also strive to reduce background noise and distractions in critical care, as these are modifiable factors that also contribute to communication impairment.

Funding

The authors did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Declaration of competing interest

The authors declare that there are no conflicts of interest.

Appendix A. Search strategy

Supplementary data to this article can be found online at https://doi.org/10.1016/j.tacc.2020.08.006.

References

[1] T. Jefferson, C.B. Del Mar, L. Dooley, E. Ferroni, L.A. Al-Ansary, G.A. Bawazeer, M.L. van Driel, S. Nair, M.A. Jones, S. Thorning, J.M. Conly, Physical interventions to interrupt or reduce the spread of respiratory viruses, Cochrane Database Syst. Rev. (2011) CD006207.
[2] T. Jefferson, R. Foxlee, C. Del Mar, L. Dooley, E. Ferroni, B. Hewak, A. Prabhala, S. Nair, A. Rivetti, Physical interventions to interrupt or reduce the spread of respiratory viruses: systematic review, BMJ 336 (2008) 77–80.
[3] W.H. Seto, D. Tsang, R.W.H. Yung, T.Y. Ching, T.K. Ng, M. Ho, L.M. Ho, J.S.M. Peiris, Advisors of Expert SARS group of Hospital Authority, Effectiveness of precautions against droplets and contact in prevention of nosocomial transmission of severe acute respiratory syndrome (SARS), Lancet 361 (2003) 1519–1520.
[4] M. Ippolito, F. Vitale, G. Accurso, P. Iozzo, C. Gregoretti, A. Giarratano, A. Cortegiani, Medical masks and respirators for the protection of healthcare workers from SARS-CoV-2 and other viruses, Pulmonology (2020), https://doi.org/10.1016/j.pulmoe.2020.04.009.
[5] C.E. Colton, Respirator Classification, Routledge Handbooks Online, 2017.
[6] A.A. Chughtai, H. Seale, C.R. MacIntyre, Availability, consistency and evidence-base of policies and guidelines on the use of mask and respirator to protect hospital health care workers: a global analysis, BMC Res. Notes 6 (2013) 216.
[7] J.H. Lange, The best protection, CMAJ (Can. Med. Assoc. J.) 168 (2003) 1524.
[8] V.H.Y. Ip, R.V. Sondekoppam, T.J.P. Özelsel, B.C.H. Tsui, COVID-19 pandemic: international variation of personal protective equipment and infection prevention and control guidelines, Anesth. Analg. (2020), https://doi.org/10.1213/ANE.0000000000004941.
[9] Public Health England, COVID-19 Personal Protective Equipment (PPE), 2020. https://web.archive.org/web/20200512170952/https://www.gov.uk/government/publications/wuhan-novel-coronavirus-infection-prevention-and-control/covid-19-personal-protective-equipment-ppe. (Accessed 12 May 2020).
[10] H. Seale, J.-S. Leem, J. Gallard, R. Kaur, A.A. Chughtai, M. Tashani, R. MacIntyre, "The cookie monster muffler": perceptions and behaviours of hospital healthcare workers around the use of masks and respirators in the hospital setting, Int J Infect Control 11 (2014) 1.
[11] H.J. Chapman, B.A. Veras-Estévez, J.L. Pomeranz, E.N. Pérez-Then, B. Marcelino, M. Lauzardo, Perceived barriers to adherence to tuberculosis infection control measures among health care workers in the Dominican republic, MEDICC Rev 19 (2017) 16–22.
[12] K.-L. Khoo, P.-H. Leng, I.B. Ibrahim, T.K. Lim, The changing face of healthcare worker perceptions on powered air-purifying respirators during the SARS outbreak, Respirology 10 (2005) 107–110.
[13] L.J. Radonovich Jr., J. Cheng, B.V. Shenal, M. Hodgson, B.S. Bender, Respirator tolerance in health care workers, J. Am. Med. Assoc. 301 (2009) 36–38.
[14] H. Nelson, USA: objections to protective respirators, Lancet 340 (1992) 1088.
[15] M. Brouwer, E. Coelho, C. das, D. Mosse, L. Brondi, L. Winterton, F. van Leth, Healthcare workers' challenges in the implementation of tuberculosis infection prevention and control measures in Mozambique, PloS One 9 (2014), e114364.
[16] L.A. Nickell, E.J. Crighton, C.S. Tracy, H. Al-Enazy, Y. Bolaji, S. Hanjrah, A. Hussain, S. Makhlouf, R.E.G. Upshur, Psychosocial effects of SARS on hospital staff: survey of a large tertiary care institution, CMAJ (Can. Med. Assoc. J.)

170 (2004) 793–798.
[17] G.A. Miller, G.A. Heise, W. Lichten, The intelligibility of speech as a function of the context of the test materials, J. Exp. Psychol. 41 (1951) 329–335.
[18] R.R. McNeer, C.L. Bennett, D.B. Horn, R. Dudaryk, Factors affecting acoustics and speech intelligibility in the operating room: size matters, Anesth. Analg. 124 (2017) 1978–1985.
[19] H.H. Fawcett, Speech transmission through respiratory protective devices, Am. Ind. Hyg. Assoc. J. 22 (1961) 170–174.
[20] International Electrotechnical Commission (IEC), IEC 60268-16:2011, Sound System Equipment - Part 16: Objective Rating of Speech Intelligibility by Speech Transmission Index, 2011.
[21] K.M. Coyne, A.T. Johnson, G.H. Yeni-Komshian, C.R. Dooly, Respirator performance ratings for speech intelligibility, Am. Ind. Hyg. Assoc. J. 59 (1998) 257–260.
[22] S.R. Atcherson, L.L. Mendel, W.J. Baltimore, C. Patro, S. Lee, M. Pousson, M.J. Spann, The effect of conventional and transparent surgical masks on speech understanding in individuals with and without hearing loss, J. Am. Acad. Audiol. 28 (2017) 58–67.
[23] T.W. Reader, R. Flin, B.H. Cuthbertson, Communication skills and error in the intensive care unit, Curr. Opin. Crit. Care 13 (2007) 732–736.
[24] Y. Donchin, D. Gopher, M. Olin, Y. Badihi, M. Biesky, C.L. Sprung, R. Pizov, S. Cotev, A look into the nature and causes of human errors in the intensive care unit, Crit. Care Med. 23 (1995) 294–300.
[25] M. Williams, N. Hevelone, R.F. Alban, J.P. Hardy, D.A. Oxman, E. Garcia, C. Thorsen, G. Frendl, S.O. Rogers Jr., Measuring communication in the surgical ICU: better communication equals better care, J. Am. Coll. Surg. 210 (2010) 17–22.
[26] M.J. Coates, A.S. Jundi, M.R. James, Chemical protective clothing; a study into the ability of staff to perform lifesaving procedures, J Accid Emerg. Med. 17 (2000) 115–118.
[27] J. Schumacher, J. Arlidge, D. Dudley, J. Van Ross, F. Garnham, K. Prior, First responder communication in CBRN environments: FIRCOM-CBRN study, Emerg. Med. J. 36 (2019) 456–458.
[28] K.M. Coyne, D.J. Barker, Speech intelligibility while wearing full-facepiece air-purifying respirators, J. Occup. Environ. Hyg. 11 (2014) 751–756.
[29] D.M. Caretti, L.C. Strickler, Speech intelligibility during respirator wear: influences of respirator speech diaphragm size and background noise, Am. Ind. Hyg. Assoc. J. 64 (2003) 846–850.
[30] S. Hah, T. Yuditsky, K.A. Schulz, H. Dorsey, A.R. Deshmukh, J. Sharra, Evaluation of Human Performance while Wearing Respirators, U.S. Department of Transportation Federal Aviation Administration, 2009.
[31] L.L. Mendel, J.A. Gardino, S.R. Atcherson, Speech understanding using surgical masks: a problem in health care? J. Am. Acad. Audiol. 19 (2008) 686–695.
[32] L.J. Radonovich Jr., R. Yanke, J. Cheng, B. Bender, Diminished speech intelligibility associated with certain types of respirators worn by healthcare workers, J. Occup. Environ. Hyg. 7 (2010) 63–70.
[33] Institute of Medicine, Committee on the Development of Reusable Facemasks for Use During an Influenza Pandemic, Reusability of Facemasks during an Influenza Pandemic: Facing the Flu, The National Academies Press, Washington, DC, 2006.
[34] A.J. Palmiero, D. Symons, J.W. Morgan 3rd, R.E. Shaffer, Speech intelligibility assessment of protective facemasks and air-purifying respirators, J. Occup. Environ. Hyg. 13 (2016) 960–968.
[35] A.T. Johnson, W.H. Scott, C.G. Lausted, K.M. Coyne, M.S. Sahota, M.M. Johnson, G. Yeni-Komshian, D.M. Caretti, Communication using a telephone while wearing a respirator, Am. Ind. Hyg. Assoc. J. 61 (2000) 264–267.
[36] A.T. Johnson, W.H. Scott, K.M. Coyne, F.C. Koh, J.E. Rebar, Telephone communications with several commercial respirators, Am. Ind. Hyg. Assoc. J. 62 (2001) 685–688.
[37] F. Thomas, C. Allen, W. Butts, C. Rhoades, C. Brandon, D.L. Handrahan, Does wearing a surgical facemask or N95-respirator impair radio communication? Air Med. J. 30 (2011) 97–102.
[38] A.T. Johnson, Respirator masks protect health but impact performance: a review, J. Biol. Eng. 10 (2016) 4.
[39] R. Udayasiri, J. Knott, D. McD Taylor, J. Papson, F. Leow, F.A. Hassan, Emergency department staff can effectively resuscitate in level C personal protective equipment, Emerg. Med. Australasia (EMA) 19 (2007) 113–121.
[40] J. Schumacher, J. Arlidge, F. Garnham, I. Ahmad, A randomised crossover simulation study comparing the impact of chemical, biological, radiological or nuclear substance personal protection equipment on the performance of advanced life support interventions, Anaesthesia 72 (2017) 592–597.
[41] D. Coniam, The impact of wearing a face mask in a high-stakes oral examination: an exploratory post-SARS study in Hong Kong, Lang, Assessment Q. 2 (2005) 235–261.
[42] S.A. Zollinger, H. Brumm, The Lombard effect, Curr. Biol. 21 (2011) R614–R615.
[43] M. St Pierre, G. Hofinger, C. Buerschaper, R. Simon, Crisis Management in Acute Care Settings: Human Factors, Team Psychology, and Patient Safety in a High Stakes Environment, second ed., Springer, 2011.
[44] J.D. Abeysekera, H. Shahnavaz, Ergonomics assessment of selected dust respirators: their use in the tropics, Appl. Ergon. 18 (1987) 266–272.
[45] A.S. Baig, C. Knapp, A.E. Eagan, L.J. Radonovich Jr., Health care workers' views about respirator use and features that should be included in the next generation of respirators, Am. J. Infect. Contr. 38 (2010) 18–25.
[46] M.E. Gosch, R.E. Shaffer, A.E. Eagan, R.J. Roberge, V.J. Davey, L.J. Radonovich Jr., B95: a new respirator for health care personnel, Am. J. Infect. Contr. 41 (2013) 1224–1230.
[47] K.A. Pollard, L. Garrett, P. Tran, Bone Conduction Systems for Full-Face Respirators: Speech Intelligibility Analysis, Army Research Laboratory, 2014.
[48] J.J. Hajicek, N. Myrent, Q. Li, D. Barker, K.M. Coyne, Protocols for improved understanding of situational awareness effects of head-borne PPE, in: 2010 IEEE International Conference on Technologies for Homeland Security (HST), 2010, pp. 127–131.
[49] National Institute for Health and Care Excellence, Emergency and Acute Medical Care in over 16s: Service Delivery and Organisation, 2018 (Chapter 32) Structured patient handovers, https://web.archive.org/web/20200630131216/https://www.nice.org.uk/guidance/ng94/evidence/32structured-patient-handovers-pdf-172397464671. (Accessed 30 June 2020).